AD-A223 061

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 23220.1-EL
6a. NAME OF PERFORMING ORGANIZATION University of Maryland; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Dr. S. Das Sarma, Dept. of Physics, University of Maryland, College Park, MD 20742-4111	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211, Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-85-K-0233
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211, Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) Electron-Phonon Interaction and Transport in Artificially Made Semiconductor Microstructures

12. PERSONAL AUTHOR(S) Dr. Sankar Das Sarma

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM Oct 1985 TO Dec 1989	March 1990	15

16. SUPPLEMENTARY NOTATION The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Electron-phonon interactions, inelastic scattering, plasmon phonon coupling, dynamical screening, ballistic transport, quantum wells, hot electrons, ultra small devices, energy

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Our research accomplishments under this contract cover a wide area of transport and electron-phonon interaction processes in artificially made semiconductor microstructures including a complete theory for picosecond relaxation phenomena and hot electron energy los in semiconductor quantum wells and heterostructures, a theory for inelastic scattering in ballistic hot-electron transistors, a theory for elementary excitations in low dimensional semiconductor microstructures, a theory for the quasiparticle properties of semiconductor microstructures and a theory of band-gap renormalization. Our theory includes plasmon-phonon coupling, dynamical screening slab and interface phonon effects. Our calculated results are in excellent quantitative agreement with the available experimental results in semiconductor microstructures. Our quantitative theoretical results will be of use to a wide class of next-generation transistor and opto-electronic devices which are based on artificial semiconductor microstructures. These include high-electron-mobility-transistors, ballistic hot-electron transistors, resonant tunneling diodes and various non-linear opto-electronic devices.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

Electron-Phonon Interaction and Transport in Artificially Made Semiconductor Microstructures

FINAL REPORT

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March 1990

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DAAG29-85-K-0233
(Proposal No. 23220-EL)

University of Maryland

Final Report for ARO Contract No. DAA29-85-K0233 (PI: S. Das Sarma)

Under our current ARO Contract (No. DAAG29-85-K0233) we have published (or have had accepted for publication) 68 papers in refereed journals in the last four years. In addition, there are about 10 papers which have either been submitted for publication or are under preparation. It is a reasonable expectation that we will have about 80 publications under the sponsorship of this contract. We have been invited to give about two dozen invited talks in major international conferences including the Hot Electron Conference (1987), APS March Meeting (1988), the Gordon Conference (1987), the Two-Dimensional Conference (1987), the Superlattice and the Microstructure Conference (1987), the Ultrafast Phenomena Conference organized by the SPIE and the OSA (1988), various NATO Conferences (1990), International Device Conference (1989), etc. In addition, we have been invited to write a number of major review articles on "Electron-Phonon Interaction in Semiconductor Microstructures" by the World Scientific Press, by the Academic Press and by the Plenum Press. A list of the published papers and invited conference talks under the ARO contract is provided at the end of this section. We also have produced four Ph.D.'s and six Masters' degrees on research done under the ARO Contract. Very recently, we have been asked to contribute a chapter on plasmon phonon coupling effects in ultrafast phenomena in semiconductor microstructures to a book on ultrafast processes being published by the Academic Press (edited by J. Shah of AT&T Bell Labs). This book (December 1990) will have articles by the leading researchers in this important subject area.

A significant feature of the work we have done under the current ARO contract is that most of the specific problems proposed by the Principal Investigator in the original ARO proposal (# 23220-EL) submitted in 1985 have been solved by during the three-year contract period. This includes fundamental and important issues such as picosecond hot carrier relaxation problem, dynamical screening and plasmon-phonon coupling effects in hot electron relaxation in III-V semiconductor microstructures, slab modes and interface phonon effects in semiconductor microstructures, theory of polar scattering in heterojunctions and quantum wells, etc. Below we provide a very short description of the highlights of our specific research accomplishments under the ARO contract. The numbers in parenthesis after each subsection below refer to the publication list given at the end of this section.

1). Hot electron relaxation in polar semiconductors. We have developed a fairly complete quantitative theory for hot electron relaxation in polar semiconductors (both microstructural and bulk) within the electron temperature model. Our calculated results agree well with the measured energy loss rates[12,13] in GaAs bulk[14] and quantum well systems, both for steady- state electric field heating and photoexcitation experiments in the picosecond relaxation regime. Our theory includes hot phonon effect, quantum degeneracy, dynamical screening, plasmon-phonon and quasiparticle-LO phonon coupling effects. For quantum wells and heterostructures, it also includes electronic quantization (into subbands) and, very recently, phonon slab mode effects. Our theory gives a very good account of the experimentally measured electron energy loss rates to polar optical phonons, and, should have significant implications for device simulation in this regime. (Publication # 22, 24, 32, 34, 37, 40.)

2) Self-energy effects in ultrafast processes. In doing our research on the picosecond relaxation problem we have discovered that many-body coupling between quasiparticles and LO-phonons could lead to very significant effects on the hot electron transport properties. We find that quasiparticle renormalization of the bare LO-phonon mode leads to satellite LO-phonon peaks at quasiparticle energies. These quasiparticle-like LO-phonon excitations carry very little spectral weight (typically 10^{-3} - 10^{-5} of the bare phonon mode) and are, under normal circumstances, not of any consequence. But, at low temperatures, they play

a very significant role in the hot electron relaxation process since these are the only LO-phonon modes that can be thermally occupied at low temperatures. Since thermal occupancy is an exponential process, it is clear that at some low temperatures, these novel quasiparticle-like LO-phonon modes are the main loss mechanism for the hot electrons in semiconductors. Our explicit detailed calculations bear out this simple physical picture and we think that we have identified an important "missing loss" mechanism[15,16] at low temperatures which have earlier been mentioned in the literature. (Publication # 37, 40.)

3) Polar scattering effects in microstructural transport properties. We have calculated the polar scattering rate as a function of temperature, carrier density and the quantum well width in GaAs microstructures. The calculated results should be of direct relevance to the device simulation of high-speed modulation-doped field-effect transistors. (Publication # 15, 17, 26.)

4) Ballistic hot-electron transistors. We have done some preliminary calculations of inelastic mean-free paths in the ballistic hot-electron transistor (or, the hot-electron spectrometer) recently developed[2] by the AT&T Bell Labs (Hayes and Levi) and the IBM (Heiblum) groups. Our calculation includes the dynamical screening and plasmon-phonon coupling effects on the electron-phonon interaction. (Publication # 12, 32.)

5) Collective electronic effects in artificially structured materials. We have investigated a number of different aspects of electronic collective modes in artificially made semiconductor microstructures. Perhaps the most interesting of these is our theory of plasmons in artificially made aperiodic (both quasiperiodic and random) multilayer structures. We showed that a study of plasmon dispersion and spectral weight via the light scattering Raman spectroscopy could be successfully used to study the important problem of Anderson localization. In particular, plasmons in Fibonacci and other quasiperiodic superlattices[17] could,

in principle, show very interesting dispersion including Cantor set spectrum and fractal properties. We have also made a theoretical investigation of the magnetoexciton spectra of quasiperiodic semiconductor superlattices. Some of our theoretical predictions in this subject have already been verified experimentally. (Publication # 3, 10, 33.)

6) Elementary excitation in semiconductor multiquantum well and superlattice systems. We have developed a quantitative theory based on the RPA to describe the elementary excitation spectrum of quasi-two dimensional systems. In particular, the intra- and inter- subband excitations (both quasiparticle-like and collective) in quantum wells and multilayer structures have been calculated in details keeping the coupling between in-plane and out-of-plane excitations which is important at non-zero wavevectors. A specific and somewhat surprising finding is that the coupling between intra- and inter-subband excitations could have quite significant effect on the elementary excitation spectra of low dimensional structures. Our calculated spin-density and charge-density excitations are in excellent agreement with the available light scattering and infrared spectroscopic experimental results from the AT&T Bell Labs[18], the Max Planck Institute[19] and the University of Hamburg[20] groups. (Publication # 14, 16, 20, 31.)

7) Electronic properties of quantum wire structures. We were among the first groups to calculate the electronic structure of quasi-one dimensional quantum wires using a variational approximation. We have also obtained the elementary excitation spectra and the screening properties of quantum wire systems. We have also carried out a preliminary calculation of the optical properties of a lateral superlattice made with quantum wire arrays. This system is expected to be important in the next-generation infrared detection technology. (Publication # 8, 11, 13, 18, 28, 30.)

8) Transport in quasi-one dimensional systems. We have developed a quantum formalism to calculate the Drude transport properties of quasi-one dimensional semiconductor wires. Our theory which is based on the Kubo formula includes self-consistent level-broadening and screening, intersubband scattering and finite temperature effects. Our theoretical results are in reasonable agreement with the only available experimental results[7] from the MIT JSEP program of Warren et al. carried out under the ARO sponsorship. Consistent with experiment, we find that at low temperatures and for high mobility samples, it should be possible to see quantum oscillations in the mobility of a quasi-one dimensional system. (Publication # 18, 30.)

9) Fluctuating transport in mesoscopic systems. We are one of the really active theory groups in this very exciting novel area of condensed matter physics.[10] Phase coherence effects and lack of ensemble averaging lead to interesting fluctuations in low temperature transport properties of small systems (e.g. universal *conductance fluctuation phenomenon*, Aharonov-Bohm effect). We have carried out numerical simulation of such transport fluctuations in all three regimes of transport properties: Strongly localized variable-range-hopping regime; weak scattering, diffusive and weakly localized universal conductance fluctuation regime; and, the ballistic regime. We have numerically studied the transition from one to two- dimensional behavior in the variable-range-hopping transport fluctuations of small MOSFET's. Our results are in good agreement with the experimental results[21] of the IBM group. We also predict a novel Aharonov-Bohm effect in the phonon-assisted variable-range-hopping transport of small highly disordered rings.[22] We are also the first group to calculate universal conductance fluctuation results using the recursive Kubo formula. (Publication # 21, 27, 28, 29, 30, 41, 44, 45.)

10) Vertical transport in superlattice minibands. Very recently (basically in the last one year) experimental observation of carrier miniband transport along the superlattice growth direction (the so-called "vertical transport") has been reported by a number of groups[23-25] using a variety of experimental techniques. Even though the currently available experimental data are preliminary, these are very exciting (and much more experimental results will be forthcoming in the near future) both from the fundamental electronic properties and device applications viewpoints. It may be worthwhile to point out that the original suggestion[26] for the superlattice by Esaki and Tsu in 1969 was motivated by the possibility of interesting physics associated with vertical miniband transport. It has taken almost twenty years of advances in materials growth and fabrication techniques for us to be able to observe this phenomenon! Encouraged by these experimental results we have developed a quantum formalism (neglecting interference effects) to study miniband transport in superlattices. We find that the standard Bloch-Boltzmann picture of Drude transport breaks down in superlattice minibands since level broadening, temperature, chemical potential and the miniband width all have comparable energies and, therefore, the quasiparticle picture is invalid. Our numerical results are in excellent agreement with the experimental data.[23] (Publication # 39.)

11) Magnetic field effects on transport properties of microstructures. Application of an external magnetic field has often led to new phenomena (e.g. Quantum Hall effect, Aharonov-Bohm effect) in microstructures. Equally important is the fact that experiments under an external magnetic field lead to a better understanding of the various scattering processes in microstructures. Motivated by various experimental results, we carried out a number of theoretical studies of magnetic field effects on transport properties. Notable among these is a study of the size quantization effect on the excitation gap in the fractional quantum Hall

effect. This work allowed for the first real quantitative comparison between theory and experiment in fractional quantum Hall effect and is used extensively by experimentalists. Earlier estimate of the excitation gap without the subband quantization effect was wrong by a factor of four! We also pointed out that the discrepancy between experiment and theory on magnetopolarons in GaInAs heterostructure is probably due to the role of interface phonon modes in the electron-phonon interaction. We also calculated the phase coherence length in two dimensions by solving the electron-phonon self-energy exactly and obtained detailed agreement with experiment in weak localization experiments. Finally, we calculated the transport and single-particle lifetimes in semiconductor microstructures and showed that in high-mobility modulation- doped systems, the transport lifetime could be larger than the single- particle lifetime by as much as two orders of magnitude! Thus even very high mobility structures could have lot of forward scattering and, thus, considerable broadening. Our theoretical predictions have been verified experimentally by the IBM group.[27] (Publication # 5, 9, 21, 27, 29.)

12) Quantum tunneling. We have carried out very detailed theoretical calculations of the quantum tunneling problem in microstructures under high magnetic fields. As a first application of this theory we show that the quantum Hall effect could be affected in narrow quasi-one dimensional systems. This has already been verified experimentally. (Publication # 42, 43, 44, 45, 46.)

13) Resonant tunneling. We have developed a detailed theory for the elastic scattering effect on electronic resonant tunneling through the double-barrier-single-quantum-well structure. Such scattering could arise from either the ionized impurity scattering or the interface roughness scattering and has traditionally been discussed phenomenologically using a Breit-Wigner type formula. Our theory is in good agreement with existing experimental results and makes a

specific prediction about a novel type of electron focusing effect in resonant tunneling. (Publication # 58, 65.)

14) Parabolic quantum wells. We have carried out extensive electronic structure calculations of GaAs-$Al_xGa_{1-x}As$ parabolic quantum wells with a goal toward understanding their transport and optical properties. Our fully self-consistent numerical calculations include the effect of an external magnetic field and incorporates exchange-correlation corrections and the spatial variation of electron effective mass in such structures. The calculated results are in excellent agreement with the available transport and optical experiments. (Publication # 59.)

15) Band-gap renormalization in quantum wells. We have developed a detailed quantitative theory for the many-body band-gap renormalization in semiconductor quantum wells induced by electron-electron and electron-phonon interaction. Accurate quantitative information about band-gap renormalization is essential for the operation of many non-linear optoelectronic devices. Our theory shows that the band-gap renormalization in quantum wells is a universal function of dimensionless electron density and well width. Our calculated results are in excellent quantitative agreement with experimental results. (Publication # 51, 68.)

Even though we have done some other theoretical calculations (e.g. effect of impurity scattering on plasmon linewidths in semiconductors, a hydrodynamic theory of electronic linear response), the above items serve to provide an overview of our research accomplishments under the ARO contract. The technical details can be found in the actual publications, a list of which follows this paragraph. We believe that we have actually solved all the problems proposed in our original proposal No. 23220-EL submitted in 1985. We have shown an ability to attack the most important frontier problems in the subject and to come up with some theoretical guidelines to understand the experimental results. A significant feature of our research is that it is inspired by experimental work and, in turn, our specific predictions have motivated a lot of experimental work. It is perhaps no surprise that our work is widely cited in the experimental literature.

Publications under the ARO Contract (published or accepted for publication):

1. Path Integral Study of Localization in the Generalized Polaron Problem (B. A. Mason and S. Das Sarma), Phys. Rev. B 33, 1418 (1986).

2. Theory of Finite Temperature Screening in a Disordered Two-Dimensional Electron Gas (S. Das Sarma), Phys. Rev. B. 33, 5401 (1986).

3. Proposed Experimental Realization of Anderson Localization in Random and Incommensurate Artificial Structures (S. Das Sarma, A. Kobayashi, and R. E. Prange) Phys. Rev. Lett. 56, 1280 (1986).

4. Theory of Helium Adsorption on Noble Metals (S. M. Paik and S. Das Sarma), Solid State Commun. 58, 223 (1986).

5. Excitation Gap in the Fractional Quantum Hall Effect: Finite Layer Thickness Correction (F. C. Zhang and S. Das Sarma), Phys. Rev. B (Rapid Communication) 33, 2903 (1986).

6. On the Saturation of the Van der Waals Potential Near a Metal Surface (S. Das Sarma and S. M. Paik), Chem. Phys. Lett. 126, 526 (1986).

7. Phonon-Induced Shifts in Shallow Donor Energy Levels of Two-Dimensional Quantum Wells and Heterostructures (B. A. Mason and S. Das Sarma), Phys. Rev. B 33, 8379 (1986).

8. Ground-State Variational Wavefunction for the Quasi-one Dimensional Semiconductor Quantum Wire (W. Y. Lai and S. Das Sarma), Phys. Rev. B (Rapid Communications) 33, 8874 (1986).

9. Frequency-Shifted Polaron Coupling in GaInAs Heterojunctions (S. Das Sarma), Phys. Rev. Lett. 57, 651 (1986).

10. Plasmons in Aperiodic Structures (S. Das Sarma, A. Kobayashi, R. E. Prange), Phys. Rev. B34, 5309 (1986).

11. Electronic Properties of Quasi-one Dimensional Quantum Wires (W. Y. Lai, S. Das Sarma, X. C. Xie, A. Kobayashi), 18th International Conference on the Physics of Semiconductors (Stockholm, 1986), p. 509.

12. Aspects of Electron-Phonon Interaction in Semiconductor Heterostructures and Superlattices (S. Das Sarma, W. Y. Lai, A. Kobayashi), ICPS '86 (Stockholm), p.651.

13. Plasmon Band Structure in a Lateral Multiwire Semiconductor Superlattice (W. Y. Lai, A. Kobayashi, S. Das Sarma), Phys. Rev. B34, 7380 (1986).

14. Plasmon Linewidth in Metals and Semiconductors: A Memory Function Approach (D. Belitz and S. Das Sarma), Phys. Rev. B34, 8264 (1986).

15. Theory of Polar Scattering in Semiconductor Quantum Structures (B. A. Mason and S. Das Sarma), Phys. Rev. B35, 3890 (1987).

16. Proposed Experiment for the Observation of Surface Plasmon in Superlattices (J. K. Jain and S. Das Sarma), Phys. Rev. B (Rapid Communications) 35, 918 (1987).

17. Transport Relaxation Time of a Two-Dimensional Electron Gas due to Scattering by Surface Acoustic Waves (C. E. Leal, I. C. D. Cunha Lima, A. Troper, and S. Das Sarma), Phys. Rev. B35, 4095 (1987).

18. Calculated Transport Properties of Quasi-one Dimensional Inversion Lines (S. Das Sarma and X. C. Xie), Phys. Rev. B (Rapid Communications) 35, 9875 (1987).

19. Non-local Theory for Surface Plasmon Excitation in Simple Metals (S. Das Sarma), Phys. Rev. B. 36, 3026 (1987).

20. Elementary Electronic Excitations in Quasi-two Dimensions, (J.K. Jain and S. Das Sarma), Phys. Rev. B. 36, 5949 (1987).

21. Transition from One- to Two-Dimensional Fluctuating Variable Range Hopping Conduction in Microstructures (X.C. Xie and S. Das Sarma), Phys. Rev. B (Rapid Communications) 36, 4566 (1987).

22. Electron Energy Loss Rate of Electrons in Quantum Wells (J.R. Senna and S. Das Sarma), Solid State Commun. 64, 1397 (1987).

23. Dynamical Effects on Phonon Emission in a Polar Electron Gas (S. Das Sarma, A. Kobayashi, and W.Y. Lai), Phys. Rev. B. 36, 8151 (1987).

24. Hot Electron Relaxation in GaAs Quantum Wells (S. Das Sarma, J.K. Jain, and R. Jalabert), Phys. Rev. B. 37, 1228 (1987).

25. Phonon Renormalization Effects in Quantum Wells (S. Das Sarma and M. Stopa), Phys. Rev. B. 36, 9595 (1987).

26. Theory of Electron-Polar Phonon Scattering Rates in Semiconductor Microstructures (B.A. Mason and S. Das Sarma), J. Superlattices and Microstructures (in press).

27. The Inelastic Phase Coherence Time in Thin Metal Films (D. Belitz and S. Das Sarma), Phys. Rev. B (Rapid Communication) 36, 7701 (1987).

28. Conductance Fluctuations in One Dimensional Quasicrystals (S. Das Sarma and X.C. Xie), Phys. Rev. B. 37, 1097 (1987).

29. Aharonov-Bohm Effect in the Hopping Conduction of a Small Ring (X.C. Xie and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 36, 9326 (1987).

30. Aspects of Transport Properties of Quasi-one Dimensional Electron Systems (X.C. Xie and S. Das Sarma), Surf. Sci. 196, 89 (1988).

31. Elementary Collective Excitations in Multilayered Two Dimensional Systems (J.K. Jain and S. Das Sarma), Surf. Sci. 196, 466 (1988).

32. Hot Electron Relaxation in Polar Semiconductors (S. Das Sarma, J.K. Jain and R. Jalabert), Solid State Electronics, 31, 695 (1988).

33. Magneto-excitons in Quasi-periodic Superlattices (S.R. Yang and S. Das Sarma), Phys. Rev. B 37, 4007 (1988).

34. Theory of Hot Electron Energy Loss in Polar Semiconductors: Role of Plasmon-Phonon Coupling (S. Das Sarma, J.K. Jain and R. Jalabert), Phys. Rev. B 37, 6290 (1988).

35. Effect of Phonon Self-Energy Correction on Hot Electron Relaxation in Two-Dimensional Semiconductor Systems (S. Das Sarma, J.K. Jain and R. Jalabert), Phys. Rev. B 37, 4560 (1988).

36. Diffusion of Interacting Particles in a Two Dimensional Periodic Potential (R. Jalabert and S. Das Sarma), Phys. Rev. A 37, 2614 (1988).

37. Many-Body Effects in a Non-equilibrium Electron-Lattice System: Coupling of Quasiparticle Excitations and LO-phonons (J.K. Jain, R. Jalabert and S. Das Sarma), Phys. Rev. Lett. 60, 353 (1988).

38. Extended Electronic States in One Dimensional Fibonacci Superlattice (X.C. Xie and S. Das Sarma), Phys. Rev. Lett. 60, 1585 (1988).

39. Theory of Conductivity in Superlattice Minibands (S.R. Yang and S. Das Sarma), Phys. Rev. B37, 10090 (1988).

40. Relaxation of Ultrafast Electrons in Semiconductors: Many-Body Effects (S. Das Sarma, J.K. Jain and R. Jalabert), SPIE Proc. 942, 47 (1988).

41. Universal Conductance Fluctuations Based on the Kubo Formula (X.C. Xie and S. Das Sarma), Phys. Rev. B38, 3529 (1988).

42. Tunneling in a High Transverse Magnetic Field (J.K. Jain and S. Kivelson), Phys. Rev. A36, 3476 (1987).

43. Model Tunneling Problems in a High Magnetic Field (J.K. Jain and S. Kivelson), Phys. Rev. B 37, 4111 (1988).

44. Landauer Type Formulation of Quantum Hall Transport: Critical Currents and Narrow Channels (J.K. Jain and S. Kivelson), Phys. Rev. B 37, 4276 (1988).

45. Coexistence of Aharonov-Bohm Oscillations and Quantum Hall Effect in Small Rings (J.K. Jain), Phys. Rev. Lett. 60, 2047 (1988).

46. Quantum Hall Effect in Quasi-one Dimensional Systems (J.K. Jain and S. Kivelson), Phys. Rev. Lett. 60, 1542 (1988).

47. Strong-Field Density of States in Weakly Disordered Two Dimensional Electron Systems (S. Das Sarma and X.C. Xie), Phys. Rev. Lett. 61, 738 (1988).

48. Theory of Electronic Density of States of a Two Dimensional Disordered System in the Presence of a Strong Magnetic Field (S. Das Sarma and X.C. Xie), J. App. Phys. 54, 5465 (1988).

49. Quantum Interference between Landau Levels in Quasi-One Dimensional Systems (X.C. Xie and S. Das Sarma), Solid State Commun. 68, 697 (1988).

50. Mobility Edge is a Model One Dimensional Potential (S. Das Sarma, S. He, and X.C. Xie), Phys. Rev. Lett. 61, 2144 (1988).

51. Band-Gap Renormalization in Quasi-Two Dimensional Systems by Many-Body Electron-Electron and Electron-Phonon Interactions (S. Das Sarma, R. Jalabert, and S.R.E. Yang), Phys. Rev. B. (Rapid Communications) 39, 5516 (1989).

52. Many-Polaron Interaction Effects in Two Dimensional Systems (R. Jalabert and S. Das Sarma), Phys. Rev. B. (Rapid Communications)39, 5542 (1989).

53. Role of Discrete Slab Phonons in Carrier Relaxation in Semiconductor Quantum Wells (J.K. Jain and S. Das Sarma), Phys. Rev. Lett. 62, 2305 (1989).

54. Calculated Shallow Donor-Level Binding Energies in $GaAs\text{-}A\ell_xGa_{1-x}As$ Quantum Wells (M. Stopa and S. Das Sarma), Phys. Rev. B40, 8466 (1989).

55. Calculated Heat Capacity and Magnetization of Two Dimensional Electron Systems (Q.Li, X.C. Xie, and S. Das Sarma), Phys. Rev. B. (Rapid Commun.) 40, 1381 (1989).

56. Quantum Conduction in Narrow Constrictions (S. He and S. Das Sarma), Phys. Rev. B40, 3379 (1989).

57. Collective Excitation Spectra of One Dimensional Electron Systems (Q. Li and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 5860 (1989).

58. Elastic Scattering in Resonant Tunneling Systems (H.A. Fertig and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 7410 (1989).

59. Parabolic Quantum Well Self-Consistent Electronic Structure in a Longitudinal Magnetic Field: Subband Depopulation (M. Stopa and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 10048 (1989).

60. Theory of Ballistic Electron Transport Through Quantized Constrictions (S. He and S. Das Sarma), Solid State Elec. 32, 1695 (1989).

61. Inelastic Scattering Effects on Carrier Relaxation in Quantum Well-Based Hot Electron Structures (R. Jalabert and S. Das Sarma), Solid State Elec. 32, 1259 (1989).

62. Many-Body Effects in GaAs-based Two Dimensional Electron Systems (R. Jalabert and S. Das Sarma), Surf. Sci. (in press).

63. Optical and Transport Properties of One Dimensional Quantum Wire Structures (S. Das Sarma, S. He, and Q. Li), Surf. Sci. (in press)

64. A Many-Body Theory of Energy Relaxation by an Excited Electron Gas through Optical Phonon Emission (S. Das Sarma, J.K. Jain, and R. Jalabert), Phys. Rev. B41, 3561 (1990).

65. Elastic Scattering Effects on Resonant Tunneling in Double Barrier Quantum Well Structures (H. Fertig, S. He, and S. Das Sarma), Phys. Rev. B41, 3596 (1990).

66. Inelastic Scattering in a Doped Polar Semiconductor (R. Jalabert and S. Das Sarma), Phys. Rev. B41, 3651 (1990).

67. Localization, Mobility Edges, and Metal-Insulator Transition in a Class of One Dimensional Slowly Varying Deterministic Potentials (S. Das Sarma, S. He, and X.C. Xie), Phys. Rev. B41, 5544 (1990).

68. Theory of Band Gap Renormalization in Semiconductor Quantum Wells (S. Das Sarma, R. Jalabert, and S.R.E. Yang), Phys. Rev. B. (in press).

Invited Talks in Major Conferences:

1. Invited Lecturer, "Elementary Excitations in Two Dimensions," 4th Canadian Summer Institute and Workshop on Theoretical Physics (Kingston, Ontario, Canada, Summer 1986).

2. Invited APS Symposium on "Inversion Layers with Lateral Constraints," (New York City, March 1987), Chair.

3. Invited Talk, Gordon Research Conference in Condensed Matter Physics, 1987; "Long Range Phase Coherence in Condensed Matter Systems" (New Hampshire, Summer 1987).

4. "Hot Electron Relaxation in Polar Semiconductors" (Invited Talk); 4th International Conference on Hot Carriers in Semiconductors (Boston, July 1987).

5. "Elementary Collective Excitations in Multilayered Two-Dimensional Systems" (Invited Review, with J. K. Jain); 7th International Conference on Electronic Properties of Two Dimensional Systems (Santa Fe, July 1987).

6. "Electron-Phonon Interaction in Microstructures" (Invited Review, with B. A. Mason); 3rd International Conference on Superlattices, Microstructures & Microdevices (Chicago, August 1987).

7. Invited Speaker, Workshop on High-T_c Superconductivity (University of Western Ontario, London, Canada, September 1987) "Possible Mechanisms for High-T_c Superconductivity".

8. Invited Speaker, Workshop on Femtosecond Physics in Semiconductors (Tempe, Arizona, December 1987) "Many-body Effects in Ultrafast Processes".

9. Invited Talk, Joint SPIE and OSA Symposium on Ultrafast Laser Probe Phenomena in Bulk and Microstructure Semiconductors (Newport Beach, CA, March 1988) "Many-body Effects in Ultrafast Relaxation".

10. Invited Talk, APS March Meeting (New Orleans, March 1988), "Transport in Quasi-one Dimensional Structures."

11. Chair, Session on Silicon Epitaxy, APS March Meeting (New Orleans, March 1988).

12. Invited Speaker, U.S.-Soviet Bilateral Workshop on Low Dimensional Systems (June 1988, Moscow).

13. Invited Speaker, International MMM and InterMag Conference (Vancouver, Canada, August 1988).

14. Invited Speaker, International Workshop on Mesoscopic Systems (Tel Aviv, Israel, June 1988)

15. Invited Talk, Electro-Chemical Society Symposium on Non-linear and Ultrafast Optical Phenomena (Chicago, October 1988).

16. Invited Talk, Quantum Electrical Engineering Workshop of the Theoretical Physics Institute (Minnesota, October 1988); "Mobility Edge in a Model One Dimensional Potential."

17. Chair, Session on Quantum Constrictions and Narrow Wires, International Symposium on Nanostructure Physics and Fabrication (Texas, March 1989).

18. Chair, Session on Quantum Hall Effect, APS March Meeting (St. Louis, March 1989).

19. Chair, Session on Many-Body Effects, APS March Meeting (St. Louis, March 1989).

20. Invited Speaker, Kathmandu Summer School on Theoretical Physics (Nepal, Summer 1989); "Unusual Solutions to the Usual Schrödinger's Equation."

21. Invited Talk, International Symposium on Surface Waves in Solids and Layered Structures (Bulgaria, Summer 1989): "Collective Excitations in Structured Low Dimensional Systems."

22. Invited Talk, 36th Annual AVS Symposium (Boston, October 1989) "Non-equilibrium Crystal Growth".

23. Invited Speaker, 5th International Workshop on Physics of Semiconductor Devices (New Delhi, December 1989).

24. Invited Plenary Lecturer, Brazilian Summer School on Low Dimensional Systems (Sao Carlos, Brazil, February 1990).

25. Invited Speaker, NATO Workshop on "Light Scattering in Semiconductors" (Canada, March 1990); "Excitations and Mode Coupling a Doped Polar System."

26. Chair, Related Phenomena Session, NATO Workshop on Light Scattering in Semiconductors (Canada, March 1990).

27. Chair, Session on Many-Body Theory, APS March Meeting (Anaheim, March 1990).

28. Chair, Session on Transport in Microstructures, APS March Meeting (Anaheim, March 1990).

29. Invited Speaker, NATO Workshop on "Transport in Microstructures" (Turkey, April 1990).

Ph.D's granted under ARO sponsorship

1. X.C. Xie: "Fluctuating Transport in Microstructures" (June 1988).

2. R. Jalabert: "Electron-Phonon Interaction in Semiconductor Microstructures" (September 1989).

3. M. Stopa: "Electronic Structure of Semiconductor Quantum Wells" (March 1990).

4. Q. Li: "Elementary Exciations in Quasi-one Dimensional Quantum Wire Structures"

In addition six MS degrees in physics were granted to graduate students for research done under the ARO support.